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IMPROVEMENTS IN ELECTRICAL MACHINES

This invention relates to electrical machines and in particular to insulated electrical conductors suitable for use as excitation windings on the stators of high voltage electrical machines, for example, machines operating at voltages greater than 3KV.

Known types of excitation winding for the stators of such machines generally comprise solid rectangular copper conductors which are electrically insulated from each other and from an earthed laminated steel core on which they are wound. Materials used to insulate the conductors are chosen so as to have properties - such as thickness, thermal conductivity, dielectric strength, and permittivity - which are appropriate to the size of the machine, applied voltage and temperature rise.

The power output of a rotating electrical machine (whether a motor or a generator) is a function of the properties of the laminated magnetic steel core, the excitation windings and their operating temperature. An "*output coefficient*" or "*specific torque coefficient*" of such machines is often quoted as a useful means of comparing the power outputs of machines of differing design. Its units are torque per unit volume and it may be derived by dividing the machine's power output by the volume of the stator within the air-gap periphery.

Having been the subject of industrial manufacture for over 100 years, rotating electrical machines are considered a mature product using mature technologies. Over the century of production the materials and processes used in the construction have evolved slowly resulting in a steady increase in output coefficient (about 3.0% per annum) for the most popular machines. Recently, their evolutionary progress has slowed down and has now reached a plateau, suggesting that further development is either unlikely or will be very slow.

It is necessary to externally insulate the stator windings of such machines from each other and the stator core. It is also necessary to internally insulate the windings by insulating the conductors from each other within the winding. The insulation materials presently used to perform the insulation function have only limited ability to withstand high temperatures, with modest electric strength properties and generally poor thermal conductivity. Furthermore, during operation of the machines, heat is generated due to electrical losses in the winding conductors, but the poor thermal conductivity of the insulation materials results in poor transfer of the heat, and this in turn inhibits the output coefficients of the machines on which the insulation materials are used.

Since there are only small differences between the stator winding insulation systems used currently by leading manufacturers of machines, the thermal and dielectric performance of such systems is similar. Typically, all use combinations of mica, polyester film and woven glass materials impregnated with synthetic resins. The mica is used in the form of a so-called "paper" which is supported by either polyester film or woven glass and is wrapped around the conductors to insulate them from external contact. To complete the insulation process, they are vacuum pressure impregnated with the synthetic resin (for example, an epoxide resin) as the last process after positioning the windings into the stator.

It is an object of the present invention to improve the output coefficients of electrical machines and hence reduce their capital cost per KW output of electrical energy by increasing the heat transfer capability of their stator conductor windings. This is achieved in the invention by means of a novel type of composite conductor.

According to the present invention, a composite conductor for use as a winding of a high voltage electrical machine comprises:

a plurality of strands of conductor material forming a conductor bundle which in cross-section is of generally rectangular shape, the strands being insulated from each other within the bundle,

an insulating sleeve of substantially homogeneous polymeric material surrounding the conductor bundle; the insulating sleeve also having a generally rectangular shape in cross-section and the polymeric material being filled with at least one electrically insulating filler material which conducts heat more efficiently than the polymer alone, and

conductive material forming a corona shield coating at the inner and outer surfaces of the insulating sleeve.

The conductor bundle is impregnated with a curable high-temperature resistant insulating material, such as a synthetic resin or polymer material, whereby the cured composite conductor is rendered sufficiently strong and rigid to enable its use in the windings of electrical machines.

It should be noted that the term "rectangular" as used herein includes shapes which are square (having four sides all of substantially equal dimensions) and rectangles and squares having rounded corners.

A composite conductor in accordance with the invention, by virtue of its construction and the materials it uses, provides a high efficiency winding for the stator of an electrical machine. Due to its filler material(s), the insulating sleeve not only has superior dielectric strength properties which permits operating at reduced sleeve wall thickness and/or increased electric stress, but also has much higher thermal conductivity and thermal capability (temperature resistance) than known windings. The higher thermal conductivity permits a considerable increase in the heat transfer capability from the composite conductor into the stator core, which may be cooled by heat exchange with ducted airstreams. Furthermore, insulation of the conductor strands from each other substantially reduces high frequency eddy current losses in the stator winding, and the conductive surface coating on the insulation sleeve contributes to enabling safe operation at higher electric stresses at the surface of the sleeve. The

net result of the above is that the output coefficient is substantially increased and hence the capital cost of the delivered power is substantially decreased.

Preferably, the corners of the conductor bundle's rectangular shape are radiused to minimise electrical stress concentrations. The radius dimension may be up to 5 mm., preferably between 2-3 mm., but it is preferred that the corners of the insulating sleeve are substantially rectilinear, having a radius of not more than about 1mm.

Preferably, the strands of conductor material are collectively twisted around the longitudinal centreline of the conductor bundle in a similar manner to which the strands in a rope are twisted about the longitudinal centreline of the rope. This angular/spatial transposition of the strands of conductor material longitudinally of the bundle due to its twist inherently cancels eddy currents as they arise, substantially reducing or eliminating the associated losses.

The at least one insulating filler material in the polymer insulating sleeve is preferably a metallic oxide and/or a metallic nitride.

The polymeric sleeve material preferably comprises a high temperature polymer, e.g. a polymer selected from the groups comprising fluoropolymers or aromatic polymers, and the conductive coating material for reducing electric stress variations at the surfaces of the composite conductor may comprise a graphitic or silicon-based material, preferably a high-temperature resistant polymer or paint material which has sufficient of the conductive material incorporated therein to render it conductive.

Preferably the strands of conductor material comprise copper, but other materials may be useable, such as aluminium or silver. Whatever the material from which the conductor strands are made, it is preferred they are insulated from each other by means of a coating of high-temperature resistant synthetic resin or polymer material on each strand. This may be achieved either by impregnation of the conductor bundle with a

resin or precursor polymer material in its uncured state, or perhaps more conveniently and reliably by using conductor strands that have been previously manufactured with an insulating coating before being incorporated into the conductor bundle. Both these conductor coating techniques are well known in the art.

The invention further envisages a process for making the above composite conductor, comprising the steps of:

gathering together a plurality of strands of conductor material to form a conductor bundle,

impregnating the conductor bundle with a curable high-temperature resistant insulating material, the impregnation occurring one of simultaneously with the gathering process and subsequent thereto,

applying a coating of conductive material to the exterior of the twisted conductor bundle to form a first, inner, corona shield,

extruding an insulating sleeve of homogeneous polymeric material onto the coating of conductive material on the conductor bundle, the polymeric material having been previously filled with at least one insulating filler material which conducts heat more efficiently than the polymer alone, and

applying a coating of conductive material to the outer surface of the insulating sleeve to form a second, outer, corona shield;

wherein each strand of conductor material is provided with an insulating coating by at least one of coating the strands before the formation of the conductor bundle, and coating the strands during the impregnation step.

We prefer that the conductor bundle is formed into a generally rectangular shape during or subsequent to the gathering process. We further prefer that subsequent to the formation of the conductor bundle, the bundled strands are twisted bodily about a longitudinal centreline of the bundle to form a twisted conductor bundle.

Whereas it is known to impregnate the insulating wrappings of bar conductor windings with synthetic resin after they have been assembled onto the stator, then partially or wholly to cure the resin, it is envisaged that in the present invention, impregnation occurs before the composite conductor is wound onto the stator, the composite conductor then being wound onto the stator while the resin or precursor polymer material is uncured or only partly cured. This facilitates the impregnation process while allowing easy manipulation of the composite conductor during the stator winding process before the resin is fully cured.

The invention also includes a stator for a rotary electrical machine comprising a laminated steel core provided with a plurality of radially oriented slots extending longitudinally of the stator, each slot housing a winding comprising either a plurality of turns of a single length of the above composite conductor, or a plurality of turns comprising a plurality of lengths of the above composite conductor, successive turns of the composite conductor being in contact and in radial registration with each other. The winding is retained in its slot, preferably by a high thermal conductivity, electrically insulating retaining means fixed in the radially outer end of the slot. Preferably, the retaining means is a filled polymer composition having relatively high thermal conductivity compared to the polymer in its unfilled state.

The retaining means may comprise an extrusion which is forced into the end of the slot.

It should be understood that the materials mentioned herein in connection with composite conductors according to the invention are best estimates of which materials will probably be suitable.

Exemplary embodiments of the invention will now be described with reference to the accompanying drawings, in which:

Figure 1 is a perspective view of part of the inside of a stator of a rotary electrical machine provided with a conventional winding;

Figure 2 is a cross-section of a composite conductor according to the present invention;

Figure 3 is a cross-section of an alternative composite conductor according to the present invention;

Figure 4 is a radial section through part of a stator according to the invention, showing a stator slot containing a winding comprising six turns of the composite conductor shown in Figure 2;

Figure 5 is a diagrammatic representation of a process for manufacturing a composite conductor according to the invention.

Referring to Figure 1, there is shown the inner circumference of one end of a stator 10 of an A.C. electrical machine. The stator is intended to encircle the rotor (not shown) of the electrical machine. As is conventional, the stator body is composed of a large number of steel laminations and is formed with a large number of radially oriented slots 12 which extend longitudinally of the stator body.

Each slot 12 houses an excitation winding 14, successive "turns" 14A, 14B of which contact each other and are in radial registration within their slot. The windings are retained in their slots by wedges 16, made of a suitable polymer insulation material, such as filled epoxide resin. During manufacture of the stator, wedges 16 are forced into position within the mouths of the slots 12.

The loops or "turns" of the windings each comprise solid rectangular copper conductor bars 14A, 14B which are pre-formed to the correct shape to enable their installation into the stator slots. The conductor bars are electrically insulated from each other and from the earthed steel core by wrappings of mica paper on polyester support film, the wrappings being pressure-impregnated with epoxide resin and cured later.

To enable the construction of the stator winding 14 from pre-formed lengths of conductor bar, each turn of the winding consists of a plurality of lengths of conductor bar whose ends 15 projecting from the stator core are bent at compound angles as shown, these ends being brazed or otherwise securely joined together in electrical contact (not shown) to complete the turn. The ends of radially adjacent conductor bars 14A, 14B are bent in opposing directions.

As Figure 1 shows, where the ends of the conductor bars 14A, 14B, etc., project from the ends of the slots 12, packing blocks 18, 20 are inserted between adjacent conductor bars, packing blocks 18 being adjacent the end of the stator core and packing blocks 20 being spaced away from the stator core. Various of the packing blocks 18, 20 and the bent portions of some of the conductor bars 14A and 14B have been removed at the lower left of Figure 1 to show the construction more clearly. The packing blocks are moulded to shape, being made up from glass cloth bags containing glass mat laminate filler pieces impregnated with epoxide resin. Packing blocks 20 are bound to the adjacent conductor bars with glass fibre tape 22.

After assembly of the stator winding and insertion of the packing blocks, assembly of the stator is completed by tying the bent portions 15 of the conductor bars 14A, 14B, to support rings 24, 26 using glass fibre cord 28. The packing blocks and the support rings provide support to the ends of the conductor bars and prevent vibration during service. Finally, the stator assembly is heat-treated at an appropriate curing temperature for its resin-impregnated portions, this temperature being below that which would cause deterioration of the polyester film component of the conductor wrappings.

Turning now to Figure 2, a composite conductor 30 is shown in cross-section and is intended to be used as a stator winding of a high voltage electrical machine, thereby substituting for the wrapped solid conductor bars 14A, 14B of Figure 1. Unlike the solid conductor bars, however, the core of composite conductor 30 comprises a large

number of strands 31 of conductor material forming a conductor bundle 32. Preferably, the strands 31 of conductor material comprise copper, but other materials may be useable, such as aluminium (cheaper, but not such a good electrical conductor as copper) or silver (expensive, but a better electrical conductor). A typical dimension for an individual strand of conductor material is likely to be of the order of 0.1mm, so it will be appreciated that the number of strands 31 needed to form a conductor bundle 32 is likely to be much larger than that diagrammatically indicated in Figure 2, and their cross-sections will consequently appear smaller relative to the total cross-section of the composite conductor 30.

Conductor bundle 32, although of generally rectangular shape, has rounded corners 34 to minimise electrical stress concentrations during operation of the electrical machine. The dimensions of the conductor bundle's corner radii R are in the range 0.5 to 5 mm.; 2-3 mm. may be optimum.

To reduce high frequency eddy current losses in the stator winding, the bundle of copper strands 32 is bodily twisted around the longitudinal centreline C of the composite conductor 30 in a similar manner to which the fibres in a rope are twisted about the longitudinal centreline of the rope. It should be noted that the spatial transposition of the strands of conductor material longitudinally within the bundle due to its twist inherently cancels eddy currents as they arise.

An insulating sleeve 36 of high temperature polymer material (e.g., a fluoropolymer or an aromatic polymer) surrounds the conductor bundle. In accordance with the invention, the polymer is homogeneously filled with an insulating material which conducts heat more efficiently than the polymer alone. This is explained further below. The insulating sleeve has a rectangular shape in cross-section, but unlike the shape adopted for the conductor bundle, it is preferred that the corners of the insulating sleeve are not substantially rounded, i.e. the long and short sides of the insulating sleeve meet substantially at right angles. However, there may be a small radius present,

say up to about 1mm., due to the manufacturing process and the need to apply a corona shield coating evenly to the surface of the insulation sleeve. The total width W and height H of the insulating sleeve 36 is substantially uniform in the lateral and lengthwise directions of the composite conductor. The sleeve's wall thickness T1 is similarly uniform, except of course in the regions adjacent the rounded corners 34 of the conductor bundle 32.

Thickness T1 should ideally be as small as possible consistent with adequate electrical insulation properties, because a thin wall for the sleeve 36 enables more rapid conduction of heat away from the bundle of conductor strands 32 and also allows a larger conductor bundle to be included in the composite conductor for the same overall size of composite conductor. The latter point is illustrated by reference to Figure 3, which shows an alternative embodiment of the invention in which the thickness T2 of the sleeve is about twice that of thickness T1 in Figure 2. It will be noticed that the number of conductor strands 31 that can be included in the composite conductor is much less in Figure 3 than in Figure 2.

Ordinary polymer sleeves for electric cables are extruded onto the conductor or conductor bundle by means of an extrusion head through the centre of which runs the conductor to which the sleeve is applied. This is a well known and understood process. A polymer sleeve having a wall thickness of about 0.1mm can be produced by known extrusion processes and it is preferred that the thickness of the polymer sleeve in the invention (excluding the corner regions) should be in the range 0.4 to 2.00mm. For example, a typical value for T1 could be about 0.5mm, preferably 0.65mm, and a typical value for T2 could be about 1mm.

In order to permit operation of the composite conductor 30 with as small a value of T1 as possible, the invention provides that the polymeric material from which the sleeve 36 is made is homogeneously compounded with one or more powdered materials which conduct heat more efficiently than the polymer alone. These materials may be

metallic oxide or metallic nitride fillers, such as aluminium oxide or aluminium nitride. As a result, the insulating sleeve 36 not only has superior dielectric strength properties which permits operating at reduced thickness, but also has much higher thermal conductivity and temperature resistance than known windings. The approximate volume ratio of polymer to filler material may be 10% to 75%.

To obtain low eddy current losses and hence good electrical efficiency of the composite conductor 30 in its role as a current carrying stator winding in an electrical machine, the individual conductor strands 31 in the conductor bundle 32 are insulated from each other according to the invention. As discussed in more detail below, this can be achieved by impregnating the conductor bundle with a synthetic resin material, such as an epoxide resin, and/or using conductor strands that have been previously provided with an insulating coating. Such pre-coated wires are routinely used in the production of windings for small electrical machines, being wound straight onto a rotor or stator.

Before or during the application of the insulating sleeve to the conductor bundle a thin coating of conductive material e.g., a graphitic or silicon-based material, such as a carbon-filled high-temperature resistant polymer, is applied so as to form a corona protective shield on the inside surface of the of the extruded polymer, i.e., at the interface between the insulating sleeve and the conductor bundle. During or after the application of the insulating sleeve to the conductor bundle, a thin coating of the same or a similar conductive material is applied to the outside surface of the insulating sleeve so as to form a corona protective shield thereon. The external coating is indicated by the dotted line 38 surrounding the sleeve 36 in Figure 2 (the inner corona shield is not shown). The purpose of the conductive coating material is to equalise the electric stresses on the surface of the composite conductor during operation of the electrical machine and thereby avoid localised breakdown of the insulation afforded by the insulating sleeve 36. We have found that both inside and outside surfaces of the insulating sleeve should be provided with the conductive corona shield coating to

provide good equalisation of the electric stresses at the surface of the composite conductor.

A suitable thickness for the inner and outer corona shields is in the range about 0.1 to 0.3mm, preferably at the lower end of this range. As already stated, a polymer film of this thickness is known to be extrudable and therefore the inner and outer corona shields may be applied by means of extrusion, as hereafter described. Alternatively, the inner corona shield may be applied by winding a thin tape of the conductive material onto the conductor bundle before the insulating sleeve is applied thereto and the outer corona shield may be applied by winding a thin tape onto the outside of the insulating sleeve after the insulating sleeve has been applied to the conductor bundle. As yet a further alternative, the corona shields may be applied in the manner of a coat of paint; for instance, before application of the insulating sleeve to the conductor bundle, the latter may pass through a bath of the corona shield material held as a suspension or solution in a suitable liquid and after the insulating sleeve has been applied it may similarly be passed through such a bath. However, in such a process it will be necessary to ensure that the inner corona shield has adequately dried or cured to form a flexible high temperature resistant coating before application of the insulating sleeve to the conductor bundle occurs. Similarly, the outer corona shield coating must have dried or cured to form a flexible high temperature resistant coating before further handling of the composite conductor occurs, such as winding it into the slots of the electrical machine.

To facilitate the impregnation process while allowing easy manipulation of the composite conductor during the process of producing the winding on the stator core, the composite conductor is impregnated before the composite conductor is wound onto the stator and fully cured only after it has been wound onto the stator. As explained later, impregnation may occur at the time when the individual strands of conductor material are gathered together and consolidated into the conductor bundle, before application of the insulating sleeve. We prefer then to partially cure the resin, so

that the composite conductor is still flexible enough to be wound directly onto the stator, with optional intervening storage on a drum for later use. The completed stator is heat-treated at a temperature below that at which deterioration of the filled polymer sleeve and the corona shield occurs, thereby fully curing the resin to make the finished stator winding rigid.

Turning now to Figure 4, it is shown how the composite conductor 30 of Figure 2 may be used to form a complete stator winding. The stator 40 of a rotary electrical machine comprises a laminated steel core 42 provided with radially oriented slots extending longitudinally of the stator. In the broken-away sectional view, only one of the slots 44 is shown. It houses a winding 46 comprising a plurality of turns or loops of the composite conductor 30. Each turn conveniently comprises a single length of the composite conductor, or alternatively, two or more shorter lengths of composite conductor may be spliced together to complete one turn. As can be seen, successive turns 30A, 30B, etc, of the composite conductor are in contact and in radial registration with each other. It should be noted that the rectangular shape of the composite conductor minimises air voids in the finished winding, enabling geometrically exact production of the winding without pre-forming of rigid bar conductors, as was necessary in the prior art. The winding is retained in its slot 44 by a high thermal conductivity, electrically insulating retaining wedge 48 fixed in the radially outer end of the slot. The wedge may be an extrusion comprising a filled polymer material, such as an epoxide resin, and may be driven into the slot from the end face of the stator.

In connection with the rectangular shape of the conductor bundle and the insulating sleeve, it should be particularly noted that besides the better packing characteristics of the composite conductors in the machine slots, the extra thickness T3-T1 (Figure 2) of the insulation at the corner of the conductor bundle effectively reduces the electric stress at the corner to approximately the same value as that on the flat sides of the

conductor bundle. Such reduction in peak electric stresses in the windings contributes to an ability of the machine to operate at higher loadings.

During production of the stator, the inherent flexibility provided by the polymer insulation sleeve, the thin corona shield coatings, the thin conductor strands and the uncured or partially cured resin on the conductor strands, permits ease of positioning of the conductor in the slots in the stator core to form a winding. However, after heat-treatment to cure the resin (curing being at a temperature lower than the temperature at which the filled polymer insulation sleeve and the corona shield coatings begin to deteriorate), the rigidity provided by the fully cured resin on the conductor strands 31 enables the finished stator winding to withstand the operational impressed forces. Note that where the composite conductor winding 30 is not within the slots 44, it may be supported by support rings and packing blocks as shown for the known arrangement in Figure 1.

A possible process for making the composite conductor will now be described with reference to Figure 5. At the left of Figure 5, many pre-insulated wire strands 31 of copper or other conductor material are drawn together from storage reels (not shown) and passed through a bundle forming head I to produce a conductor bundle 32. Within the head I are means, well known in the art of cable-making, whereby the strands 31 are brought together, formed into a bundle and the bundle is bodily twisted around the centreline of the bundle. At the same time as the strands 31 are being formed into a bundle, the bundle is impregnated with an epoxy resin or similar binding and strengthening agent resistant to high temperatures; alternatively, this impregnation process may be a pressure impregnation process, as known, the pressure impregnation being accomplished immediately after the conductor bundle has been formed and either within the head I or following it. The final process within head I (which may in practice be carried out in a separate head, not shown) is to finally form and consolidate the conductor bundle into the required rectangular shape of the present invention by passing it through a suitably shaped die.

The head I is heated so as to partially cure the resin as the conductor bundle passes therethrough, thereby producing a conductor bundle which has good cohesion, yet is still sufficiently flexible to be wound onto a large diameter storage drum S1 for later use. Alternatively, the partly cured bundle passes straight on as indicated through the centre of an annular die in extruding head II, whereby a conductive filled polymer film is extruded onto the outside of the conductor bundle 32 to form a first, inner, corona shield. Thereafter, the coated conductor bundle passes through the centre of a further annular die in extruding head III, whereby a filled polymer insulating sleeve is extruded onto the outside of the first corona shield. Effectively, this first corona shield thereby forms a conductive coating on the inner surface of the insulating sleeve. Finally, by a similar process to that described for head II, a second, outer, corona shield is applied to the insulating sleeve in extruding head IV, so completing the formation of a composite conductor 30. The composite conductor 30 can then be wound onto a large diameter storage drum S2 for later use. Alternatively, as indicated by the dashed arrow line, it can pass straight into a further manufacturing stage for producing windings for electrical machines. As mentioned previously, final curing of the conductor bundles is accomplished by heating, after the composite conductor has been fixed into the winding slots in an electrical machine, as shown in Figure 4.

It has been said above that the wire strands 31 are pre-insulated, meaning that during their manufacture they have been provided with a thin coating of suitable epoxy resin or high temperature resistant polymer, as known. However, as an alternative to the use of pre-insulated wire strands, it may be possible to rely on the resin impregnation process which occurs in head I to insulate the strands 31 from each other within the finished conductor bundle. This will be a matter for determination by routine experimentation.

Although in Figure 5 the strands are shown being gathered together into a bundle in a one-stage process, in practice, due to the large number of strands required to make a

conductor bundle, this first part of the process may require a number of parallel stages in which a number of sub-bundles are produced in corresponding bundle-producing heads, each bundle having been impregnated with resin therein as described previously, the sub-bundles then being brought together to form the final twisted rectangular conductor bundle 32.

It will be evident that the above process may be used to produce composite conductors having cross-sectional shapes other than rectangular, e.g. circular.